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Philip Kirk

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DESIGN OF A COLD FORMED SECTION
PORTAL FRAME BUILDING SYSTEM

by

Philip Kirk *

1 Introduction

Ayrshire Metal Products plc have developed a light weight, cold formed section portal frame system for small span building construction.

The system offers a new approach to the design of buildings for both industrial and agricultural applications.

The 'Swagebeam' cold rolled section (Figure 1) has been successfully used as an alternative to hot rolled steel sections in a number of applications. In particular, it is used in a storage platform system.

As a result of these uses it was apparent that the same section could be used to form portal frames. With suitable joints, a structural system could be designed which would embody all the advantages of cold rolled sections.

The Swagebeam sections are bolted back to back for columns and rafters with single sections for purlins, side rails and other secondary members. Together with a range of brackets and cleats producing 5, 10 or 15 degree roof slopes, the section proves ideal for portal frames with clear spans of between 9 and 15 metres.

The 'swages' in the section interlock with similar swages in the brackets and cleats giving economical, rigid joints requiring fewer bolts for connections.

Frame components are fully galvanised and are simple to assemble and erect, requiring minimal lifting gear.

The system is designed for total flexibility in choice of cladding and positioning of doors and windows.

* Group Product Development Manager, Ayrshire Metal Products plc,
Royal Oak Way, Daventry, Northamptonshire, NN11 5NR, England.

2 Background to Development

Ayrshire Metal Products have been closely associated with the building industry in the UK for many years. Recently they have been approached by several customers with a requirement for a light weight building frame which would fulfil a market gap between workshop or garage type structures and larger span hot rolled section portal frame buildings.

Small span frames, traditionally fabricated from hot rolled sections, had been identified as uneconomical users of steel and required expensive cranes for erection.

A cold rolled steel frame, specifically developed for this market sector, was the obvious answer.

3 Technical Developments

Swagebeam is a multi purpose beam section. Its suitability for incorporation into a building frame system was studied.

At an early stage in the development work the design of simple but effective brackets to form joints at the eaves and ridge positions was identified as the important area for investigation. First by calculation and then full scale testing, the most effective arrangement of swages and bolts was established. The inclusion of swageing in the brackets which interlock with the section proved to be the most important advance in design as it not only produces rigid joints with no slip under load, but also reduces the number of bolts required by 50%.

The result of this work was a set of brackets that are simple pressings, cheap to produce, requiring no welding or special fabrication work (Figures 2 and 3).

With the size and shape of the eaves and ridge joints established, full size portal frames were tested to destruction, proving the total system behaved as predicted by calculation.

4 Design and Materials Standards

The frame is designed in line with the requirements of BS449, Addendum No. 1 (The use of cold formed steel sections in building). This standard is of limited scope so design assumptions were verified by the full scale load tests.

The frame is analysed by elastic computer methods assuming fully rigid joints at the eaves and ridge connections.

The column bases are normally taken as pinned but fixed bases may be considered provided complete fixity is obtained (an economical method of achieving this is to cast the column base in concrete).

Purlins and side rails are designed as simply supported at the portal frame member.

Where profiled steel cladding is specified on both roof and walls, the design takes account of the stressed skin action obtained from directly fixed cladding. This eliminates the requirement for wind bracing in the building.

All steel used is of structural grade to BS2989 having a guaranteed minimum yield strength of 280 N/mm². All sections and brackets are pre-hot dip galvanised.

5 Full scale tests

Full scale testing of components and frames was carried out by the Department of Civil Engineering of the University of Salford in England, under the direction of Professor Eric R Bryan.

5.1 Stiffness and strength of joints

It is assumed in the design analysis that the eaves and ridge joints are fully rigid. It is also assumed, in calculating the maximum theoretical loads on the frames, that the moment capacity of the joints are at least equal to that of the members.

Since interlocking swages are a new concept in cold formed steel design, full scale tests on eaves and ridge joints were carried out in order to justify the above assumptions.

For these tests, short lengths of Swagebeam section used in the system were bolted to eaves and ridge brackets. These assemblies were then subjected to loads simulating the action of snow and wind load in the actual portal frame (Figure 4). Load was applied by a screw jack and measured with a load cell so that the load could still be measured even after the maximum value had been passed. The test arrangement was supported off the floor on needle bearings so that minimal resistance to horizontal movement was encountered. Restraints were positioned over the sections to prevent buckling out of plane.

In each case an initial bedding down moment of 20 KNm was applied to the joint. After removal of this load the structure was loaded up to failure in increments of 2.5 KNm or less as failure was approached.

At loads well above those which would be experienced in service the swages began to disengage. Finally, however, failure occurred in the sections just at the edge of the joint (Figure 5).

It was therefore evident that the joints were strong enough to ensure that failure occurred in the members and not in the brackets.

The failure moment of the eaves joint under simulated gravity load was 41.6 kNm and that of the ridge joint 37.3 kNm. The moment deflection curves for the two cases are shown in Figures 6 and 7. As expected, the bedding-in loading gave a greater deflection than the repeat loading to failure. The ultimate moment capacity M_c of the Swagebeam section is 32.0 kNm with a working moment of 0.65 M_c . These are marked on the graphs. It is noted that the initial portions of the curves, up to this value, are near identical to the theoretical value assuming fully rigid joints. Thereafter the actual moment-deflection curves diverge from the theoretical. However the close agreement between theoretical and measured up to the working moment indicates that the stiffness of the eaves and ridge joints can be considered to be fully rigid for elastic design.

Similar results were obtained for the joints under simulated wind loads.

5.2 Lateral support to portal frame members

The column and rafter members are assembled from two Swagebeam sections bolted back to back at purlin and side rail positions. Each section is free to buckle separately between purlins but cannot twist due to the constraint offered by the other section.

It was important to ensure that the lateral buckling behaviour of the portal members could be accurately predicted by calculation so a series of 16 tests on simply supported beams with two point loads and lateral supports at various centres were carried out.

The results of these tests indicated that lateral supports at centres greater than 1.9 metres promotes failure in the beam between the lateral supports (ie failure due to lateral buckling) and that lateral supports at centres less than 1.9m gives failure at the loading points (ie failure due to bending about the major axis).

5.3 Purlin and side rail tests

To complement the tests carried out at the University of Salford, a series of full scale loading tests to determine the strength and behaviour of Swagebeam sections used as purlins and side rails were conducted at Ayrshire Metal Products' own research and development laboratory.

Two purlins, fixed at 0.9 metre centres were loaded each time with profiled steel sheeting spanning between them.

The tests were performed in an air tight vacuum box. The pressure difference generated above and below the sheeting by a centrifugal pump, produced a controlled, uniform loading.

Both snow loading and wind suction loading was investigated.

The results of the tests simulating snow loading indicated that the failure load of the system was significantly higher than the maximum required working load in service. The recovery of the system after subjection to loads well above working load was satisfactory.

The failure loads under wind suction loading were also higher than those required to cover all exposure conditions.

The Swagebeam section has an unsymmetrical geometry and is loaded through screws in the flanges. The high torsional effects induced especially under wind suction, initiate lateral buckling at a load significantly lower than that calculated assuming loading through the shear centre. The accurate analysis to produce the limit state of lateral buckling of the section loaded in this way is complex. From a practical viewpoint the sensible precaution was to provide bracing to counteract the torsional and instability effects of loading. This has been achieved by the provision of anti-sagbars in the purlins and vertical struts and diagonal bracing in the side rails.

5.3 cont'd

Figure 8 showing failure due to wind suction indicates the anti-sagbars brace the sections against rotation at mid span with failure occurring at the quarter point where least resistance to torsion is encountered. However the system of bracing proved adequate as the sections failed at loads significantly higher than those required for use in service.

It was felt that the over design of purlins and side rails caused by using the Swagebeam sections was outweighed by the practical advantage of having a building frame system constructed from only one profile in 3 gauges plus the fact that they restrain the main portal frame members laterally and provide flush faces both inside and out for easy cladding and lining.

5.4 Tests on portal frames

Full size portal frames were tested to destruction following the component tests.

The columns were 3 metres high to eaves and the roof slope 15 degrees. The frames were tested in pairs at 2.5 metre centres, one with pinned column bases and one with fixed bases, cross braced together so that failure could not occur out of plane.

In all, 6 pairs of frames were tested with spans of 9 metres and 12 metres.

Gravity loads were applied at the purlin positions through a system of steel rods and spreader beams by two hydraulic jacks per frame. The jack loads were measured with load cells and the vertical deflection of the ridge and the horizontal displacements of the eaves were measured with dial gauges.

The test arrangement is shown in Figure 9 and a typical view of a test set-up shown in Figure 10.

The portal frames, as well as the components described previously, were tested in accordance with the new draft British Standard BS5950 Part 5 'Code of Practice for the design of cold formed sections'. Here a procedure is laid down for testing cold formed steel structures. It involves testing to three levels of load:

- 1) Preliminary test - up to unfactored load.
- 2) Acceptance test - for confirmation of general structural behaviour.
- 3) Strength test - to confirm the capacity of a structure against the required factored loads.

A test on a 12 metre span pair of frames is reported on here. A similar pattern of results were obtained in the other tests.

5.4 cont'd...

After the bedding-in load had been applied and removed, the load was taken up to the acceptance load. The deflections and recoveries on removal of this load are given in Figure 11. It is seen that the recovery is roughly 90% both for the pinned and fixed base frames; this figure is well above the required value of 80%.

Under the acceptance load ($1.15 \times \text{dead load} + 1.25 \times \text{imposed load}$) the deflections of the ridge in the pinned and fixed frames was about 67 mm (span/178) and 63 mm (span/190) respectively.

It is also seen in Figure 11 that the recoveries from the strength test load were nearly 80% (compared with the required value of 20%). This was a good result and proves the design of the interlocking swages at the joints.

The frames were then loaded to failure which occurred at 54.6 kN and 63.3 kN for pinned and fixed bases respectively. The mode of failure was compression flange buckling at the eaves followed by compression flange buckling near the apex.

Graphs of load/ridge deflection are given in Figures 12 and 13. The theoretical relationships are also given. It is seen that up to the acceptance load, the theoretical and experimental results agree well for the pinned base but not quite so well for the fixed base (this is probably due to the extreme difficulty in obtaining a completely fixed base in the laboratory).

Figure 14 shows a view along a rafter section and demonstrates the double curvature bending obtained under load.

6 Frame performance in Practice

The frame system has been designed to accommodate both industrial and agricultural building snow loadings as well as wind loading in accordance with current British Standards.

It is most cost effective for clear spans between 9 and 15 metres. Eaves heights may be up to 6 metres.

In general, under snow loading of 0.75 kN/m^2 , spans up to 13 metres can be accommodated. Under snow loading of 0.5 kN/m^2 , spans may be up to 15 metres. The minimum economical frame spacing has been set at 2.5 metres.

The four histograms in Figure 15 give an indication of portal frame centres under various loadings and column base conditions. They are only indicative as factors such as cladding type, wind loading and roof slope influence the design. These factors have been averaged for the purposes of these diagrams.

7 Construction details (see Figure 16 and 17)

7.1 Intermediate Portals

These are assembled from pre-cut, pre-punched Swagebeam sections bolted together at purlin and side rail positions in pairs with webs back to back. Double brackets are fixed between sections at the eaves and ridge positions. A T shaped base plate is fixed between sections at the column base.

7.2 Gable portals

These are constructed from single Swagebeam sections with single brackets at the eaves and ridge positions.

7.3 Purlins

Single Swagebeam sections are fixed within the depth of the portal rafters using swaged cleats. The purlin flanges point up the roof slope. Purlins are fixed at centres no greater than 1.9 metres.

7.4 Side rails

Again, these are single Swagebeam sections fixed within the depth of the portal column. Flanges point downwards.

7.5 Gable frames

Gable 'trimmer' frames are fixed to the underside of the gable rafter and to the inside of the gable column. The purpose of these is to provide total flexibility for positioning gable posts and side rails as well as door posts and headers in the gable elevation.

Gable posts are single sections, fixed to the gable rafter trimmer member using an angled cleat and to the floor slab using an L shaped base plate.

7.6 Door and window framing

These are single sections. Normally framing members are fitted so that the flush face of the web faces into the aperture.

Door and window openings can also be accommodated in the side elevations, simply by adding intermediate posts and curtailing the side rails across the opening.

8 Conclusions

The development of this product has emphasised in a practical way that cold formed sections have a very important role to play in the design of building structures, not just for secondary structural members, but in the primary framing as well. The unique ability to manufacture a complex section shape with its own exclusive strength and physical characteristics and take advantage of them means economies in the use of materials and labour can be realised. Designs which exploit the best advantages of the cold forming process are bound to become increasingly popular.

9 References

- 1) BS449: Part 2: 1969; Addendum No. 1: 1975 'The use of cold formed steel sections in building'.
- 2) BS5950: Part 5; Draft British Standard 'Code of Practice for the design of cold formed sections', 1984.
- 3) Bryan E.R., The Analysis, Design and Testing of Swagebeam Portal Frames and Components. Private report for Ayrshire Metal Products plc, 1985.

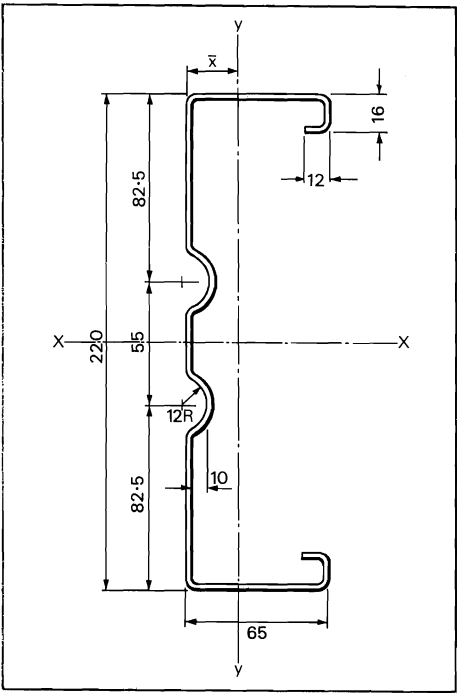


Figure 1: Swagebeam Section

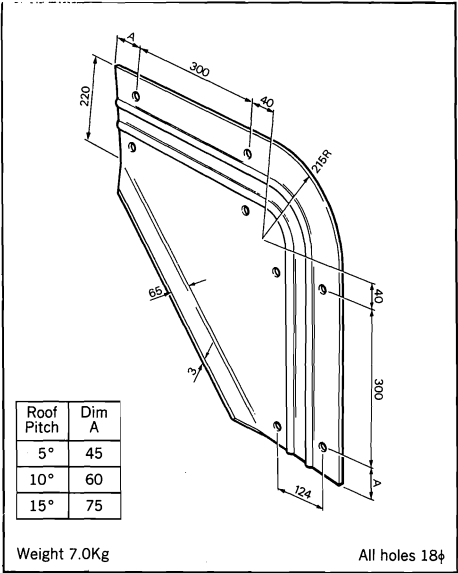


Figure 2: Eaves Bracket

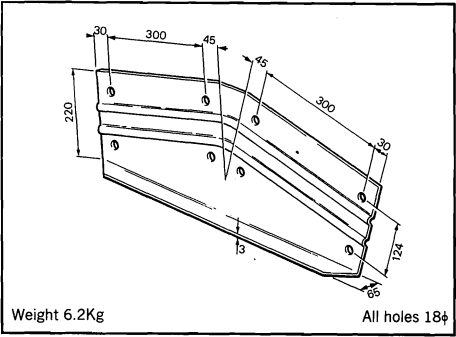


Figure 3: Ridge Bracket

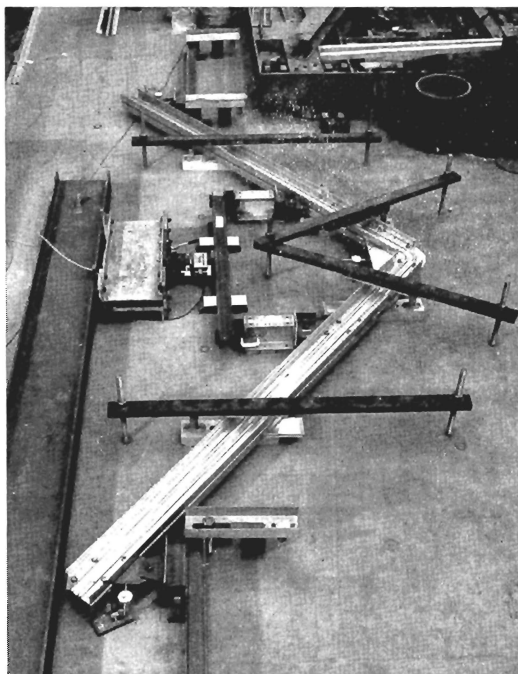


Figure 4. Eaves joint test arrangement

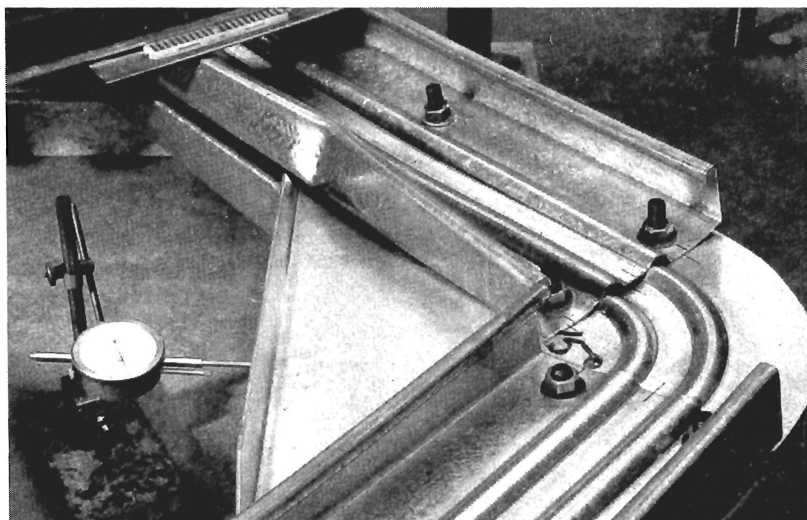


Figure 5. Eaves joint failure in section

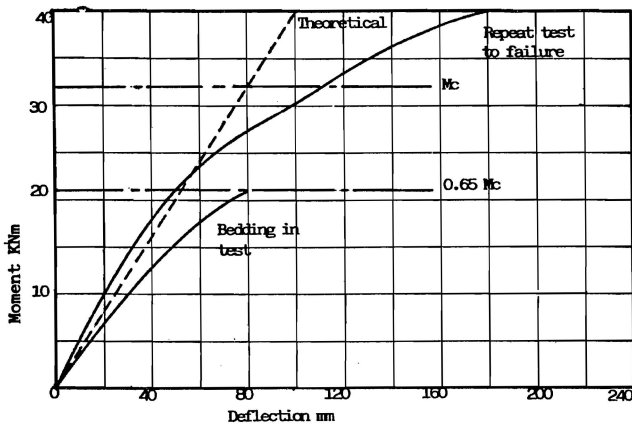


Figure 6:
Moment/deflection curve
for eaves joint under
simulated gravity loading

Figure 7:
Moment/deflection curve
for ridge joint
under simulated
gravity loading

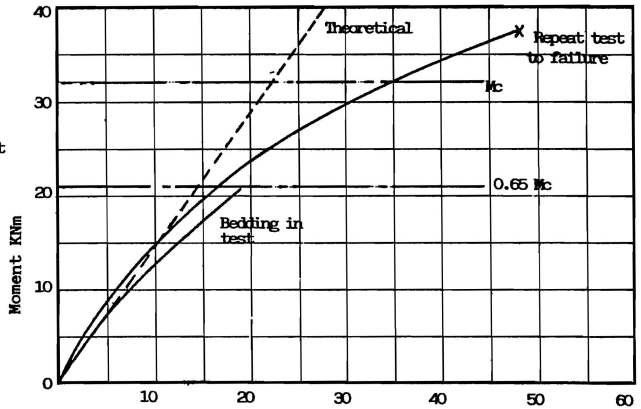


Figure 8:
Purlin test
Failure mode under wind
suction load

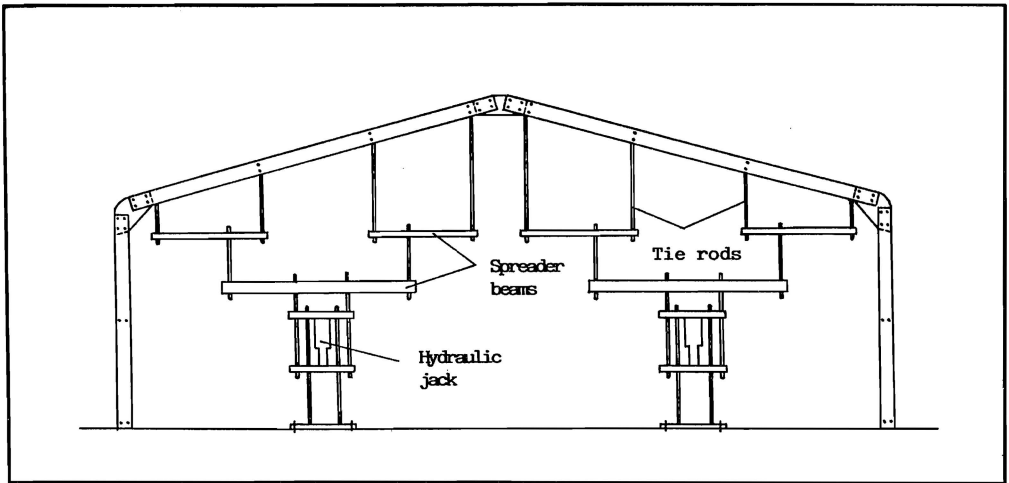


Figure 9: Test arrangement for 12 m span portal frame

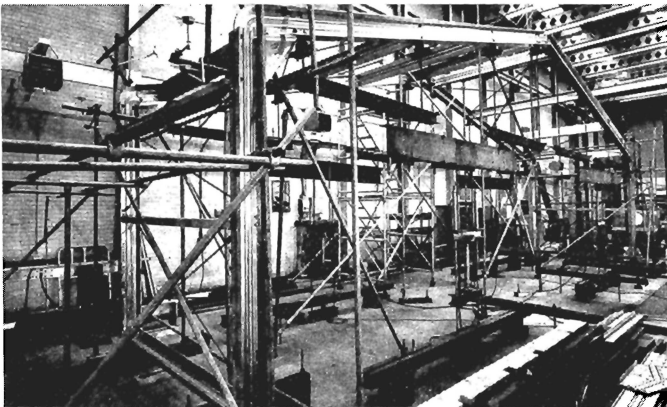


Figure 10: Typical portal frame test set-up

Test	Pinned Column Base			Fixed Column Base		
	load on frame kN	Deflection mm		load on frame kN	Deflection mm	
		Eaves	Ridge		Eaves	Ridge
Working load	30.2			35.3		
Acceptance	36.7	15.1	67.3	43.0	14.7	63.2
Unloaded		2.2	1.5		1.3	6.2
% Recovery		85%	98%		91%	90%
Strength	41.7	21.9	83.8	48.8	17.4	64.4
Unloaded		6.0	11.5		2.2	17.8
% Recovery		73%	86%		87%	72%

Figure 11: 12 m span frame test results

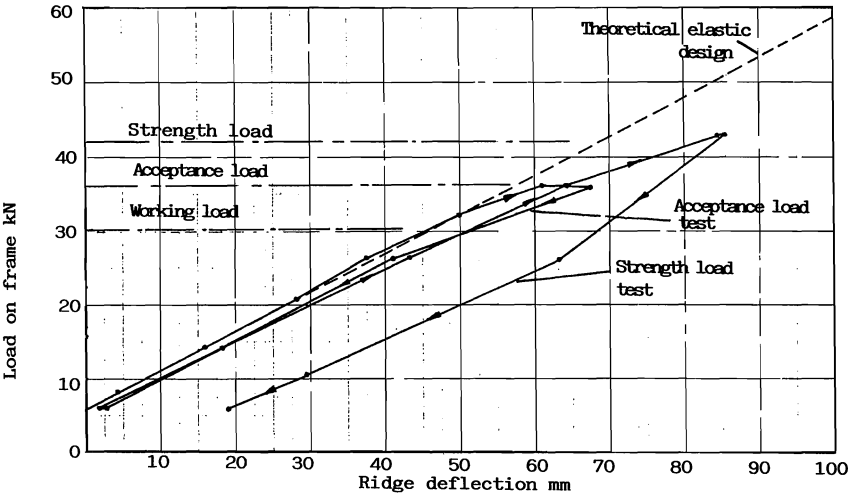


Figure 12: load/ridge deflection graph for 12 m span frame test with pinned bases

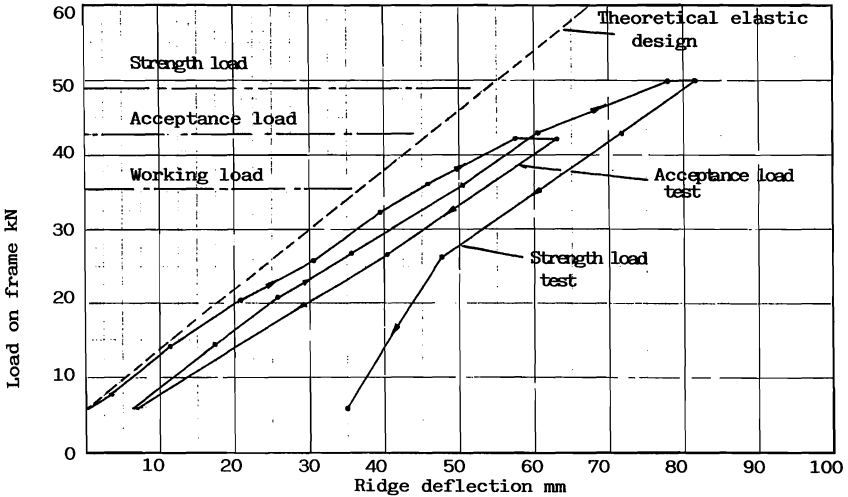


Figure 13: load/ridge deflection graph for 12 m span frame test with fixed bases

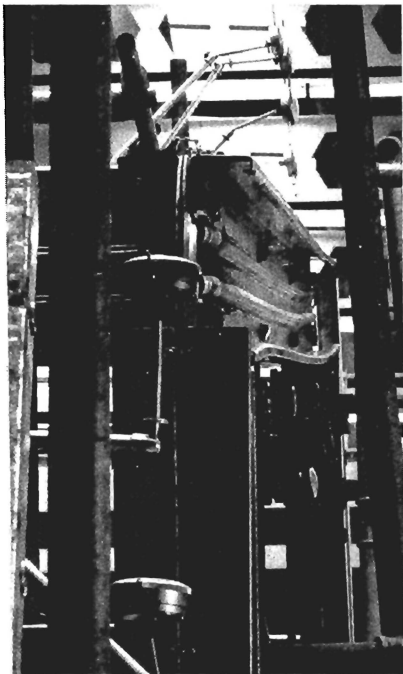
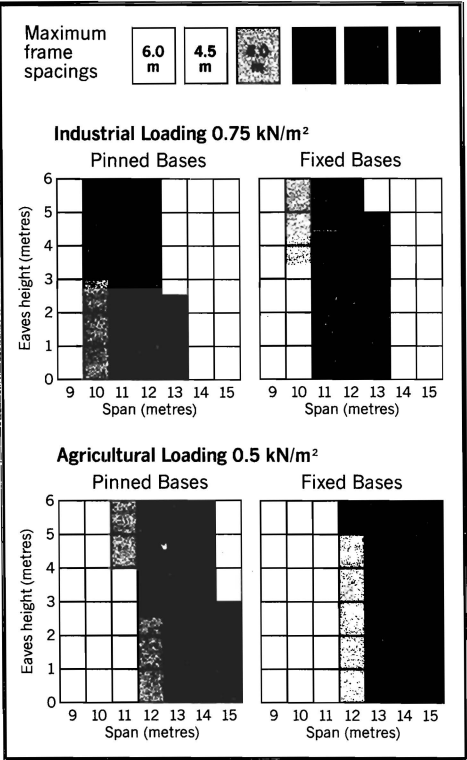


Figure 14:
View along rafter section
under load

Figure 15:
Frame performance



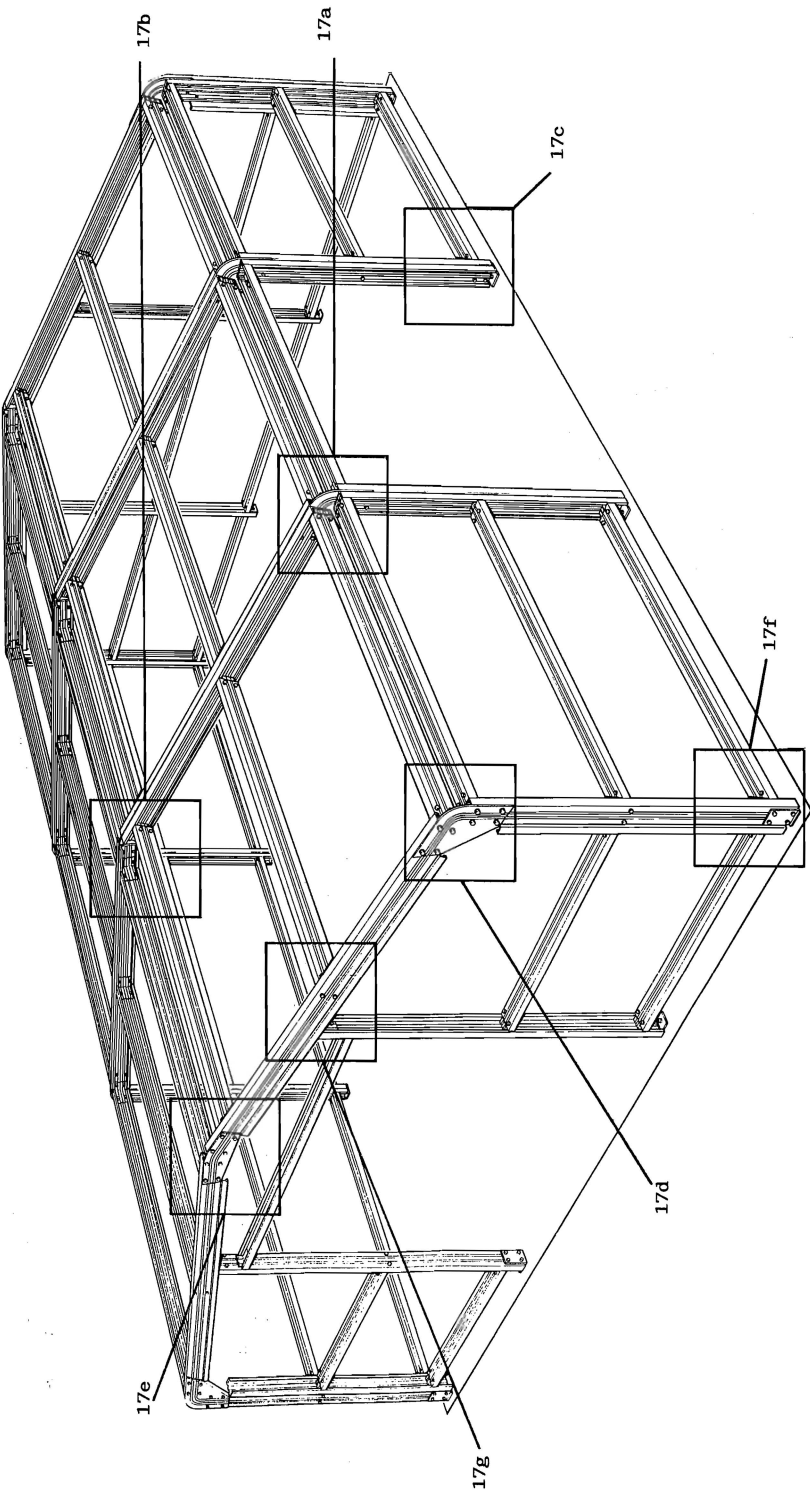
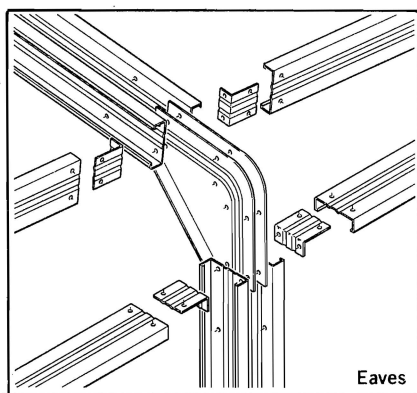
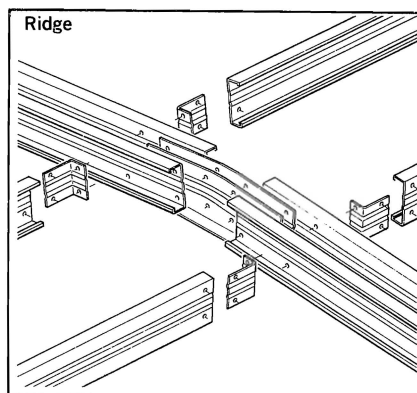


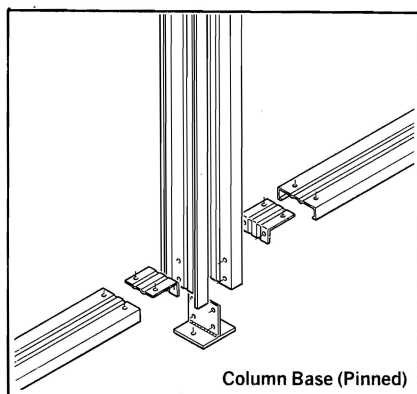
Figure 16: Swagebeam Building Frame System



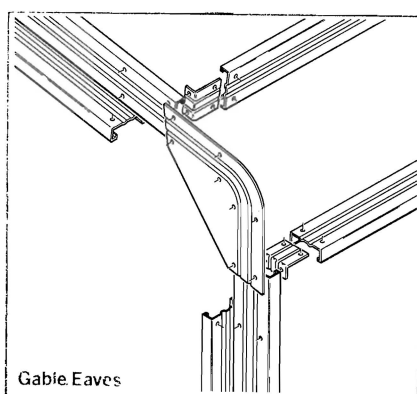
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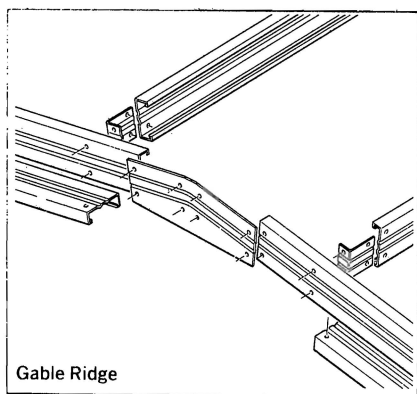
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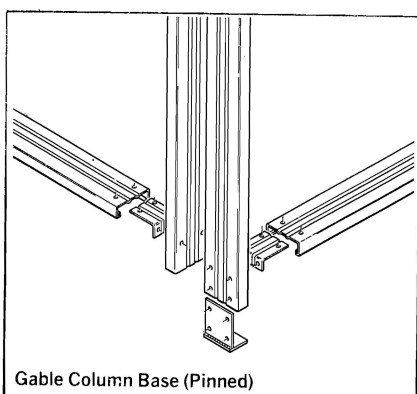
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Figure 17:

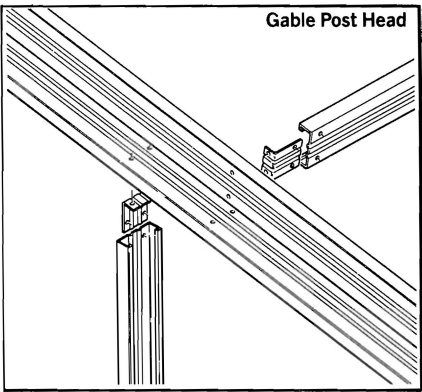


Figure 17g

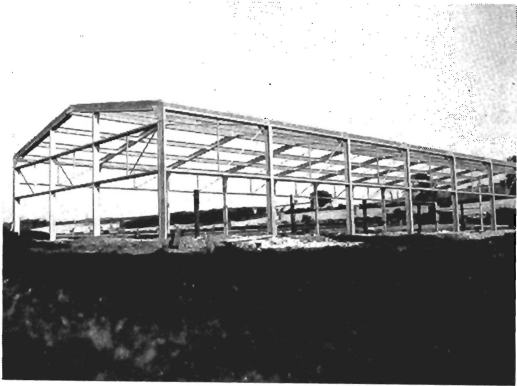


Figure 18: Swagebeam Building Frame